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# Estimating the daily peak and annual total electricity demand for cooling in Vienna, Austria by 2050

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ABSTRACT

Climate change is expected to increase temperatures worldwide and exacerbate urban heat load due to the urban heat island effect. Urban populations will be more exposed to climate change impacts on human health and mortality as compared to citizens living in rural areas. To adapt, urban populations will increase the use of air conditioning and an increase in electricity consumption for cooling is forecast.

We use a top-down method, based on the hourly electricity consumption and daily temperatures for years 2015 and 2016 for 19 European countries, to estimate the future annual demand and daily peak demand for cooling in Vienna, Austria, until 2050. The estimation is based on an ensemble average of seven downscaled climate models under two climate scenarios (RCP4.5 and RCP8.5) and includes a factor for the increase in air conditioning penetration with climate change. The estimate of peak demand, inclusion of penetration and application to a locality make the study somewhat novel.

Our results suggest that annual electrical energy for cooling in Vienna will increase from the current amount of 22 GWh/year to 95 (33–189) GWh/year by 2050 – with little difference during this time frame between RCP4.5 and RCP8.5. During the same period, peak electrical energy demand will increase to around 117 (64–191) MWh/day in 2050 from its current value of 65.5 MWh/day.

## 1. Introduction

With the increasing temperatures expected by climate change, the Intergovernmental Panel on Climate Change (IPCC, 2013; Smith et al., 2014) is warning of negative impacts on human health (WMO, 2015), increases in human mortality and negative impacts on social interactions, economic output and labour productivity (EEA, 2017). In addition the increases in temperature are expected to exacerbate urban heat load due to the Urban Heat Island effect (UHI), making the urban population even more exposed to the foreseen health impacts (Diogo and Koomen, 2014; Smith et al., 2014; Vahmani et al., 2016; EEA, 2017). As the temperature increases, air conditioning of either single rooms or whole living space is often used as a technical solution by urban populations (Lundgren and Kjellstrom, 2013; Sivak, 2013; Davis and Gertler, 2015). However, this results in a further increase in the UHI as AC

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**Table 1**
Summary from previous bottom-up and top-down studies.

| Study | Austria (year) | Vienna equivalence | Increase by 2050 |
|---|---|---|---|
| Bottom-up method | | | |
| Study | Austria (year) | Vienna equivalence | Increase by 2050 |
| Berger et al. (2014) | Not specified | Not specified – results are per m2 | 260% (without increased diffusion) |
| Pezzutto et al. (2014) | 1.3 TWh – actual (year unspecified) 8 TWh - potential | 0.26 TWh | Not specified |
| Jakubcionis and Carlsson (2017) | 3.4 TWh – potential (assuming U.S. style diffusion) | 0.68 TWh | Not specified |
| Mueller et al. (2014) | 0.94 TWh (2008) | 0.19 TWh | 33% - 55% 0.06–0.10 TWh (with increased market penetration) |
| ODYSSEE (2018) | 0.08 TWh (2015) - Residential only | 0.02 TWh | Not specified |
| Persson and Werner (2015), and Werner (2016) | 1.6 TWh (2010)<br>1) Assumed 15% penetration in service sector<br>2) Assumed residential specific demand and<br>3) Estimate of penetration in the residential sector is 2 x greater than the ODYSSEE. Online database (2018) estimate | 0.33 TWh | Not specified |
| Top-down method | | | |
| Bachner et al. (2013) | 0.06 TWh (1960–90)<br>0.108 TWh (2011 – 30)<br>0.146 TWh (2030–2050) | 0.012 TWh<br>0.023 TWh<br>0.032 TWh | 0.015 TWh (without increased market penetration) |
| Damm et al. (2017) | 0.07 TWh (2010 – 2013) | 0.015 TWh | 0.133 TWh (upper bound at 95% confidence level) (without increased market penetration) |

moves the hot air from apartments to the outside and also increases energy consumption (Kikegawa et al., 2003; Ohashi et al., 2006, de Munck et al. 2013, Lundgren and Kjellstrom, 2013; Salamanca et al., 2014; De Wit et al., 2017).

Nevertheless, the estimates of future energy consumption for AC on a per country basis are limited. There have been a series of papers in recent years that have looked at future demand for AC in European countries. These use two types of methods; top-down analyses which use daily national electricity consumption data and daily average temperatures (e.g. Giannakopoulos and Psiloglou, 2006; Blazquez et al., 2013; Töglhofer et al., 2012; Bachner et al., 2013; Damm et al., 2017; and Wenz et al., 2017), and bottom-up analyses which perform energy consumption estimates for specific building types and upscale to the national level (e.g. Berger et al., 2014; Mueller et al., 2014; Pezzutto et al., 2014; Persson and Werner, 2015; Werner, 2016; Jakubcionis and Carlsson, 2017; and ODYSSEE, 2018). The studies may or may not have included the possibility of the increasing installation of AC (market penetration). There are even fewer studies that estimate the energy consumption for AC at the city level. These studies are dominated by bottom-up method. The results from previous studies are summarised in Table 1.

In bottom-up studies, generally, the specific energy demand (kWh/m$^2$/year) for a building is modelled and this value is multiplied by the total floor area in a country and an estimate of the AC penetration rate. For Austria-specific studies, Berger et al. (2014) in a bottom-up study, based on an inventory of buildings in Vienna, estimated that average net cooling demand in 2025 would be 36.8 kWh/m$^2$. However, they do not give the cooled floor area or make an assumption about AC penetration rate. Nevertheless they estimate that the net cooling demand and peak energy demand may increase by factors of 2.6 and 1.7 respectively. Mueller et al. (2014), again a bottom-up study, found that the electricity demand in Austria for cooling is also 36.9 kWh/m$^2$/year with a gross cooled floor space of 25.6 million m$^2$ (Total demand = 0.94 TWh/year). With climate change, demand will be 33–55% more by 2050. Their model includes diffusion of air conditioning and increased floor space. Peharz et al. (2018) calculated the electricity demand of a compression chiller for an office building (60 W/m$^2$ cooling load) with 33.3 kWh/m$^2$/year.

In European-wide studies, Persson and Werner (2015) and Werner (2016) estimated that for 2010, the average specific cooling demand in Austria was 49 kWh/m$^2$ with 452 million m$^2$ floor space and an average AC penetration of 5% for a total of 1.6 TWh/year for cooling. This results in an actual cooling demand of 3.6 kWh/m$^2$. As pointed out in Werner (2016), the authors used energy estimates from district cooling systems to calculate the specific cooling demand in the service sector (kWh/m$^2$). They then assumed that residential specific cooling demand was 45% of the service sector and they also assumed an AC penetration rate of 17% and 6% for the services and residential sectors respectively. Since then, ODYSSEE (2018) has estimated that electricity consumption for cooling in the residential sector in 2015 to be 0.08 TWh with an AC penetration rate of 0.88% (0.2 kWh/m$^2$). Jakubcionis and Carlsson (2017) suggest that the penetration and cooling demand could increase by 58% and 3.4 TWh/year respectively without climate change if Austrians adopt U.S. consumer preferences for air conditioning.

As shown above, there is a large range of estimates which depends on the type of study, year of estimate and whether or not an increase in market penetration of AC with climate change is considered. In general, bottom-up estimates are significantly larger than the top-down estimates. Reasons for this are presented in the discussion at the end of the paper.

In this work, we use a top-down approach to estimate the national electricity usage for AC per floor area versus temperature relationship, introduce a method to approximate for changing AC penetration due to climate change, and apply the model to an ensemble of downscaled climate projections for two representative concentration pathways (RCP4.5 and RCP8.5) for a specific city.

By assessing the electricity usage only, we are ignoring district cooling systems that use other sources for cooling (e.g. ground or river water) In addition, we extend this method to an estimate of daily peak energy for AC. The inclusion of climate varying AC penetration and the estimate of daily peak energy for AC for a specific city, make this unique. These results can then be used to assess the impact of AC on urban climate of Vienna, as outlined in De Wit et al., 2017.

This paper has the following structure: (1) an introduction; (2) a description of the theory and calculation method; (3) presentation of the climatic and potential annual cooling and peak daily demand in Vienna; (4) a discussion of comparisons to other studies, estimate of uncertainties, and commentary on the appropriateness of the method, consumer behaviour correction, and economic influences and finally (5) a presentation of conclusions.

## 2. Material and methods

### 2.1. Methods

#### 2.1.1. Electrical energy versus temperature and AC use

The method used in this paper is an extension of the top-down methodology used in Bachner et al. (2013), Blazquez et al. (2013), Damm et al. (2017), Giannakopoulos and Psiloglou (2006), Töglhofer et al. (2012), and Wenz et al. (2017). These studies involved finding empirical relationships between daily average-temperatures and electricity consumption for a specific country. The relationships were then applied, assuming that they did not vary with climate change, to future climate data in the country. The extension used in the present paper includes the information inherent in the relationships from many countries to also predict how the relationship for an individual country will vary with climate change. We then apply this climate dependent relationship, using downscaled future climate data for a specific location (Vienna, Austria) as input, to estimate the future annual electricity consumption resulting from AC usage including increased penetration due to climate change. The improved relationship is an attempt to incorporate the increased penetration of air conditioning that may occur with climate change. In addition to annual electricity consumption, an estimate of daily peak electricity consumption is made.

Eto (1988) introduced a very simple model to predict energy consumption for cooling per unit area ($E_c$).

$$E_c = a_o + a_1(T - T_0) \text{ for T>To} \tag{1}$$

where $T$ = the outdoor air temperature, $T_o$ is a reference temperature, $a_o$ and $a_1$ are constants relating to the building envelop and user preferences.

This equation has been used as a starting point energy consumption analyses by many authors (e.g. Christenson et al., 2006; De Rosa et al., 2014; Lam, 1998; Le Comte and Warren, 1981; Sailor and Muñoz, 1997; Valor et al., 2001; Wenz et al., 2017). From this point many authors estimate factors that influence the slope, $a_1$, in the above equation (e.g. De Rosa et al., 2014; Lam, 1998; Wenz et al., 2017). When looking at individual buildings these factors include efficiency of the cooling system, and building insulation (De Rosa et al., 2014).

At the country level, there will be a mix of buildings, some which may have air conditioning and some not. Hence one must make a modification to the above equation to account for the penetration level of air conditioning. The energy demand per unit area for a mix of buildings with and without air conditioning ($E_{tot}$) is:

$$E_{tot} = (1 - P_{AC})a_o + P_{AC}E_c$$

where $P_{AC}$ is the penetration level of AC systems, and $a_o$ and $E_c$ are now the averages for the mix of buildings.

Therefore,

$$E_{tot} = a_o + P_{AC}a_1(T - T_0), \text{ for T>To} \tag{2}$$

Thus the slope of the energy versus temperature curve for the group is proportional to the penetration level of AC systems and a factor, $a_1$, which depends on the thermal envelope and design of the buildings and energy efficiency of the cooling system. For the analysis of daily energy consumption, the standard is to use cooling degree-day where $CDD = (T_{ave} - T_0)$ for a day in which $T > T_o$ Typically, $T_o = 18\,^\circ C$ (IPCC, 2001), or $65\,^\circ F$ (EPA: United States Environmental Protection Agency, 2016, NOAA: National Oceanographic and Atmospheric Administration, 2018a, USGCRP: The U.S. Global Change Research Program, 2018).

Extending this equation to the national level, first instead of country average temperature, one needs to use a weighted average of station temperatures where the weight depends on the population at the station (Valor et al., 2001). Secondly, individuals that already have air conditioning units will turn them on at different temperatures depending on their micro climate. For example, in an apartment with south-facing windows in the northern hemisphere, the occupant will turn on the AC at lower outdoor air temperatures than the occupant across the hall with north-facing windows (Ko, 2013).

Hence we will use the following equation.

$$E_{cooling} = E_{tot} - \overline{E_{tot}} = Slope_{max} * \ln(1 + e^{aT}) \tag{3}$$

where $E_{cooling}$ is defined as energy for cooling, $\overline{E_{tot}}$ is the average electricity over a temperature window where there is no AC and $Slope_{max}$, is the change in energy consumption per change in temperature when all units are turned on.The base temperature, $T_o$, no longer appears in the equation because its effect is incorporated in the value of $\overline{E_{tot}}$.

This is equation is derived from the assumption that the slope is a Smooth Transition Regression function (Moral-Carcedo and Vicéns-Otero, 2005) between slope = 0, no cooling, and $Slope_{max}$,. An examplefrom Greece (Fig. 1) clearly shows the smooth

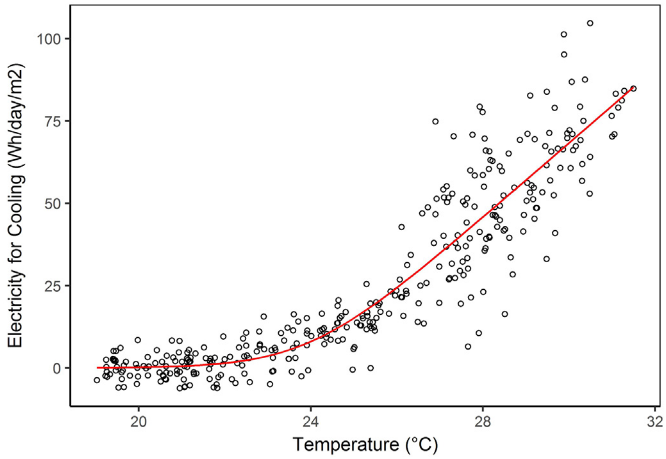


**Fig. 1.** Electricity consumption for cooling per floor area versus temperature – an example from Greece. The actual values are the open circles with the average consumption for days with 19 °C < $T$ < 20 °C removed (hence the values may be negative). It is assumed, that there is little cooling demand on those days. The modelled demand is the smooth line. $Slope_{max}$, full AC use, is reached at T > 27 °C.

transition from temperatures from little use of AC, $T$ < 22 °C, to full use of AC when $Slope_{max}$ is reached at $T$ > 27 °C.

From Eq. (2), $Slope_{max}$ is a function of penetration level and building factors. As suggested by Lam (1998) and Isaac and van Vuuren (2009) the level of AC penetration is dependent on economic and climatic factors. This partly explains why Wenz et al. (2017), for example, also suggest that the slope is dependent on economic factors. As above, since the analysis is limited to Europe, we will assume, to first order, that the penetration rate is dependent on climatic factors alone. The implications of this assumption will be considered in the discussion section.

For the climatic factor, Jakubcionis and Carlsson (2017) assume that the percentage of household is a logarithmic function of CDD. However, we suggest the climatic factor must always be increasing as one rarely uninstalls an air conditioning unit once it has been installed, and once it is installed it is in use. Hence we suggest that $CDD_{\max}$, which is maximum annual sum of CDD historically recorded may be a more appropriate indicator for the climate factor.

Therefore, we assume:

$$E_{cooling} = E_{tot} - \overline{E_{tot}} = f(CDD_{\max}) * \ln(1 + e^{aT}) \tag{4}$$

We suggest that the climate factor is more complicated when one considers the dynamics of product penetration. Bass (1969) suggested that when a new product enters the market, that there are *innovators* and *imitators*. His theory was for a homogeneous demand, but just as the room temperature and energy demand will demand on the micro climate (Ko, 2013), so will the demand for air conditioners. For example, the occupant of an apartment with south-facing windows in the northern hemisphere will likely install air conditioning before the occupant across the hall with north-facing windows assuming that they have similar financial means.

We suggest that each new $CDD_{max}$ may act like a trigger that causes a different segment of the population to consider AC as a "new" product. For example, at $CDD_{max,i}$ residents in a specific city due to local-climate factors (e.g. elevation, low wind, strong UHI, southern exposure) consider installing AC. The innovators do this almost immediately, but perhaps with a delay since the installation make take time. There may be many years without a new $CDD_{max}$ during which time the imitators purchase AC systems due to the comfort they experience when visiting an innovator. Hence, the penetration rate will increase with the time since the last change in $CDD_{max}$. Due to climate change, the probability of a new $CDD_{max}$ occurring after a period of time is increased. This time it may trigger residents living in a city with different local-climate factors (e.g. higher elevation,more winds, western exposure) to acquire new AC. A new product penetration dynamic occurs. Therefore, in order to assess the penetration rate 1) one should perform the analysis year by year and not an average over a large range of years, and 2) one should expect that $Slope_{max}$ will be a somewhat *fuzzy* function of $CDD_{max}$. We will revisit this concept later in the discussion section.

So, from where or how can you derive the $Slope_{max}$ versus $CDD_{max}$ function? On the assumption that, to first order, $Slope_{max}$ is related to penetration level only, and that penetration level is related to $CDD_{max}$, we suggest that the function should be apparent in the existing variability of $Slope_{max}$ from European countries. Hence we will perform a non-linear regression of $E_{cooling}$ versus temperature for selected European countries and look for a relationship to $CDD_{max}$ for those countries. Once the $Slope_{max}$ versus $CDD_{max}$ function has been developed, it can be used along with future climate variables to extrapolate the electricity required for cooling in a future climate.

### *2.1.2. Extension to peak electrical energy for cooling*

Policy makers, electricity system managers are not only interested in total electricity consumption per day, but also peak electricity. To approach this problem, it is assumed that the peak energy for cooling occurs around 17:00, when the daily temperature is highest and the lowest energy for cooling occurs around 03:00. As suggested by Parker (1983) and Simpson and McPherson (1996),

and measured by Akbari et al. (1992) peak cooling demand occurs in the late afternoon "when ambient temperatures reach a maximum and when people coming home from work turn on their air conditioner". The difference between the electricity demands at these two times, $E_{17}$-$E_{03}$, is used as an indicator for peak electricity energy for cooling. Of course, there are many other factors in this indicator. For example, electricity for cooking, subway systems and lighting in stores may be part of the demand at 17:00. These other factors will be much less strongly dependent on temperature than the demand for cooling and will be part of a base demand. Peak energy for cooling, we will analyse the change in $E_{17}$-$E_{03}$ with temperature. The equations above can be used replacing $E_{tot}$ with $E_{17}$-$E_{03}$. In practice we used the average electricity demand for 16:00, 17:00 and 18:00 for $E_{17}$ and the average electricity demand for 03:00, and 04:00 for $E_{03}$. The portion of the difference in demand that has little dependence on temperature (i.e. electricity for cooking, subway systems and lighting in stores) will become part of $\overline{E_{tot}}$.

### 2.2. Material

The following data are required to perform the analysis:

1) Electricity demand per hour per day (ENTSO-E: European Network of Transmission System Operators for Electricity, 2018)
2) Average daily temperatures for cities in a given country (NOAA: National Oceanographic and Atmospheric Administration, 2018b)
3) Populations of the selected cities (eurostat, 2018a)
4) Residential and commercial floor area per capita (calculated from European Commission, 2018)
5) Populations of the selected countries (eurostat, 2018b)
6) Climate data providing projected future climatic conditions for the city or country for which the prediction is being made. In this study, we used seven regional climate models spatial average for the area of Vienna based on EURO-CORDEX model runs (Jacob et al., 2014) driven by the moderate RCP4.5 and the more extreme RCP8.5 forcing scenarios (IPCC, 2013):
   a. EC-EARTH_SMHI-RCA4;
   b. EC-EARTH_KNMI-RACMO22E;
   c. EC-EARTH_DMI-HIRHAM5;
   d. CNRM_SMHI-RCA4;
   e. MPI_SMHI-RCA4;
   f. IPSL_SMHI-RCA4; and
   g. HadGEM2_SMHI-RCA4.
7) Population projections for the city or country for which the extrapolation is being made. In this study, Vienna (Statistik Austria, 2018)

We used electricity data for all days of the year except national holidays and so-called *Brückentage* – Mondays or Fridays when a national holiday occurs on the following Tuesday or preceding Thursday respectively. Fluctuations between weekdays were corrected for by subtracting the mean weekday value and adding back the seasonal average value – balancing. Summer and winter months were processed separately and outliers were removed. Subsequently, the data were limited to days with average temperature above 15 °C. For these days the baseline electricity load, defined as the mean electricity load over a temperature window which showed no systematic variation with temperature, was removed. For most countries the temperature window was between 16° and 20 °C. The resulting corrected daily electric loads are a measure of the electricity due to cooling only (Fig. 2).

The corrected daily electricity loads were then divided by an estimate of the residential and commercial floor area. These floor

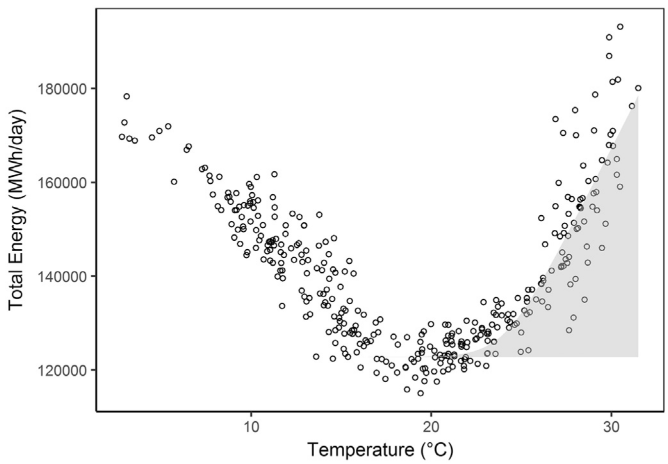


**Fig. 2.** Energy consumption versus temperature for Greece in 2015. The shaded area represents the estimated energy required for cooling.

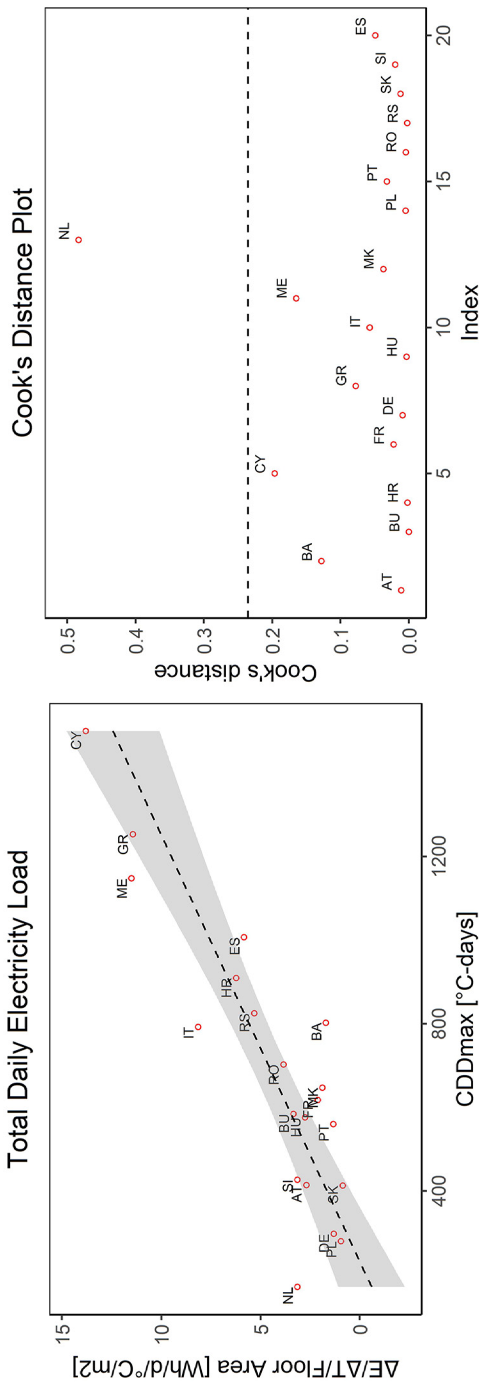


**Fig. 3.** $Slope_{max}$ versus $CDD_{max}$ for total daily electricity load in Europe in 2015 and 2016.

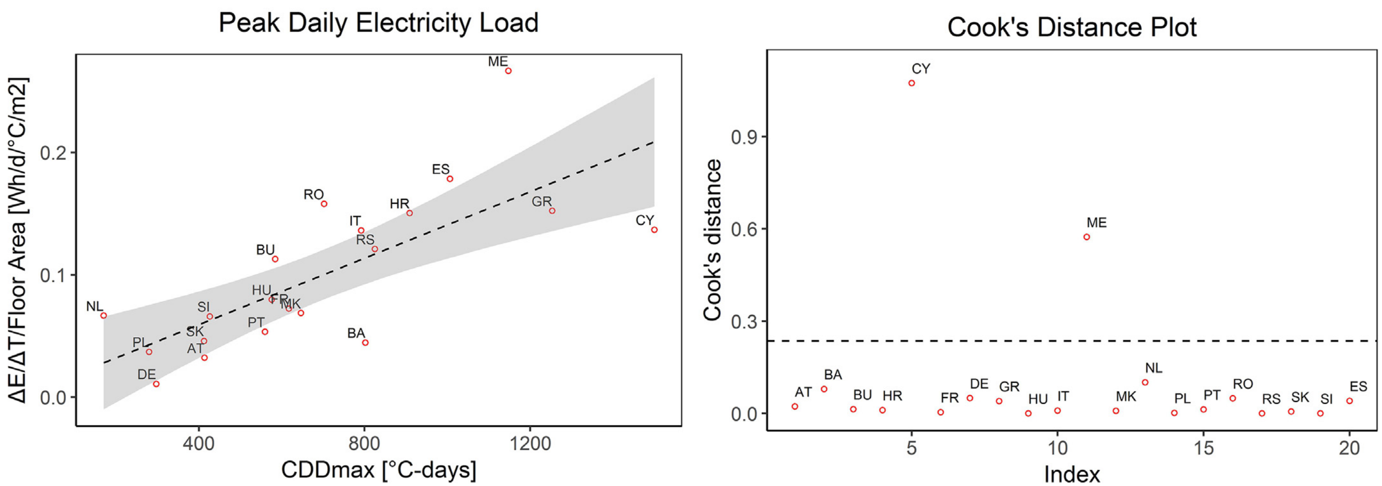


**Fig. 4.** $Slope_{max}$ versus $CDD_{max}$ for peak daily electricity load in in Europe 2015 and 2016.

areas in the analysis were estimated from the population in the year and the residential and commercial floor area per capita in 2008. After these processing steps, the data for each country for two consecutive years were combined (e.g. 2011–12, 2013–14, and 2015–16) and the parameters in a modified version of Eq. (4) were estimated using the non-linear least squares package “NLS” available in R. The modified version of Eq. (4) has a = 1. This was done to improve stability of the NLS fit for noisy data. All plots were made using the ggplot package also available in R.

## 3. Results

Fig. 3 shows the relation of $Slope_{max}$, as defined in Eq. (3), for the daily total electricity in 2015–16 versus $CDD_{max}$ for the 20 countries studied. The data show a strong linear relationship. Results from one country (NL - the Netherlands) may be considered outliers based on the Cook's distance. When it is discarded the linear regression has the form.

$$\text{Daily Total}: Slope_{max} = -3.22 + 0.0109\ CDD_{max}\ (r^2 = 0.824) \tag{5}$$

Fig. 4 displays the relation of $Slope_{max}$ to $CDD_{max}$ for the daily peak electricity in 2015–16 for all countries. The relationship is not as strong as with the daily total electricity. Two countries (CY - Cyprus and ME - Montenegro) may be considered outliers based on the Cook's distance. A linear regression based on the trimmed data results in the following relationship:

$$\text{Daily Peak}: Slope_{max} = -8.16e-04 + 1.42e-04\ CDD_{max}\ (r^2 = 0.603) \tag{6}$$

The CDD and $CDD_{max}$ in Vienna for an ensemble of downscaled climate models for RCP4.5 and RCP8.5 from 2020 to 2050 are displayed in Fig. 5 and Fig. 6. As shown, there is little difference over this time frame between the two scenarios. In both cases, the $CDD_{max}$ will increase from the current 414 °C-days to around 580 ± 40 °C-days in 2050. This is an increase of 40%, making the Vienna climate comparable to the climatic conditions currently experienced in Bulgaria or Hungary when considering high temperatures and heat. At the same time the total floor area (residential plus commercial floor area) of Vienna will increase to about 173 ± 12 $Mm^2$ from its current value of 145 $Mm^2$, since the population is expected to increase from 1,857,000 to 2,173,000 (0.4% growth p.a.)

When all of these factors are combined, we model the demand for electricity for cooling in Vienna to increase from the current amount of 22 GWh/year to 95 (33–189) GWh/year by 2050. Over this time frame there is little difference between RCP4.5 and RCP8.5 (Fig. 7).

For annual maximum peak daily energy for cooling, we estimate that it will increase to around 117 (64–191) MWh/day in 2050 from its current value of 65.5 MWh/day (Fig. 8). So the annual maximum peak daily energy for cooling in the future may be about 1.8 times greater than it currently is.

## 4. Discussion

### 4.1. Comparison to other estimates

Using our method we estimate that the total energy for cooling in Austria for 2010 and 2015 to be 0.06 TWh and 0.30 TWh respectively (or 0.1 and 0.4 $kWh/m^2$). These values are almost an order of magnitude less than many of the bottom-up results (see Table 1). However, they are in line with the results from ODYSSEE. Online database (2018). The reason for the discrepancy will be discussed in the final section of the discussion.

When one compares our results to the two top-down estimates from Bachner et al. (2013) and Damm et al. (2017) our estimate of current consumption compares favourably. Our estimate for the growth of electricity consumption is larger since we have included the increase of diffusion due to climate change, while the two previous top-down estimates did not.

### 4.2. Sources of uncertainty

Figs. 7 and 8 show that uncertainties in the estimates (95% confidence level) are rather large. Three factors contribute to the uncertainties: the floor space in Vienna, the prediction of $Slope_{max}$ due to the regression, and the variability of the climate models. The floor space in Vienna is calculated as a constant multiplied by the future population and this has an associated error of ± 7%, based on the scenarios modelled by Statistik Austria. For the total energy, the prediction of $Slope_{max}$ due to the regression has an error of ± 28%, hence for each climate model the forecasted energy estimates are ± 35%. Adding to this error are the uncertainties of the climate models themselves. By taking an ensemble average, we introduce a further 28% uncertainty due to the variability between the models. Thus, the total error in each estimate is ± 63%. The total error for the annual maximum peak daily energy is a little less ( ± 56%).

### 4.3. Possible sources of error in $Slope_{max}$: summer vacations, consumer behaviour correction, and economic influences

In this section, we discuss possible reasons for the large uncertainties, and the discrepancy between bottom-up and top-down estimates.

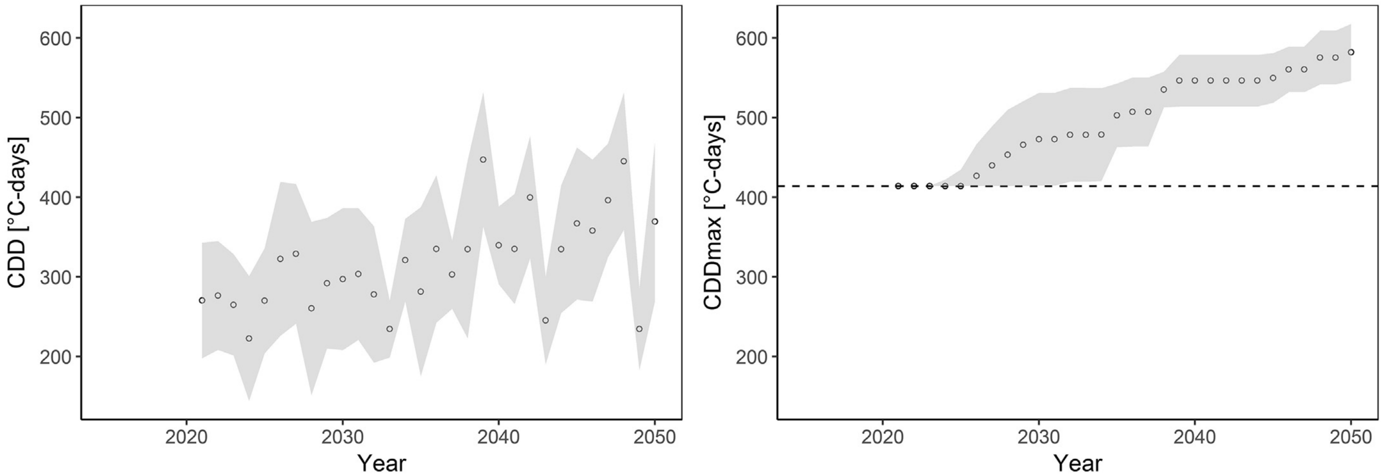


**Fig. 5.** The left plot shows the forecasted cooling degree days (CDD) in Vienna for RCP4.5. The right plotshows historical maximum of the cooling degree days ($CDD_{max}$) for RCP4.5. The open circles are the ensemble average values. The grey band is the range of values at the 95% confidence level. The dashed line is the value of $CDD_{max}$ in 2016.

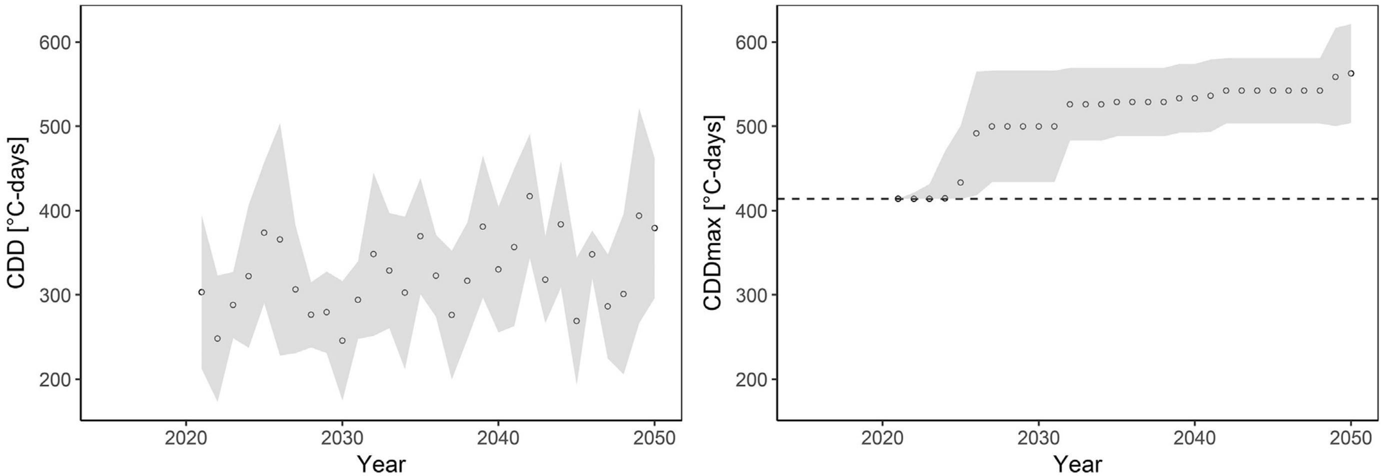


**Fig. 6.** The left plot shows the forecasted cooling degree days (CDD) in Vienna for RCP8.5. The right plot shows the historical maximum of the cooling degree days ($CDD_{max}$) for RCP8.5. The open circles are the ensemble average values. The grey band is the range of values at the 95% confidence level. The dashed line is the value of $CDD_{max}$ in 2016.

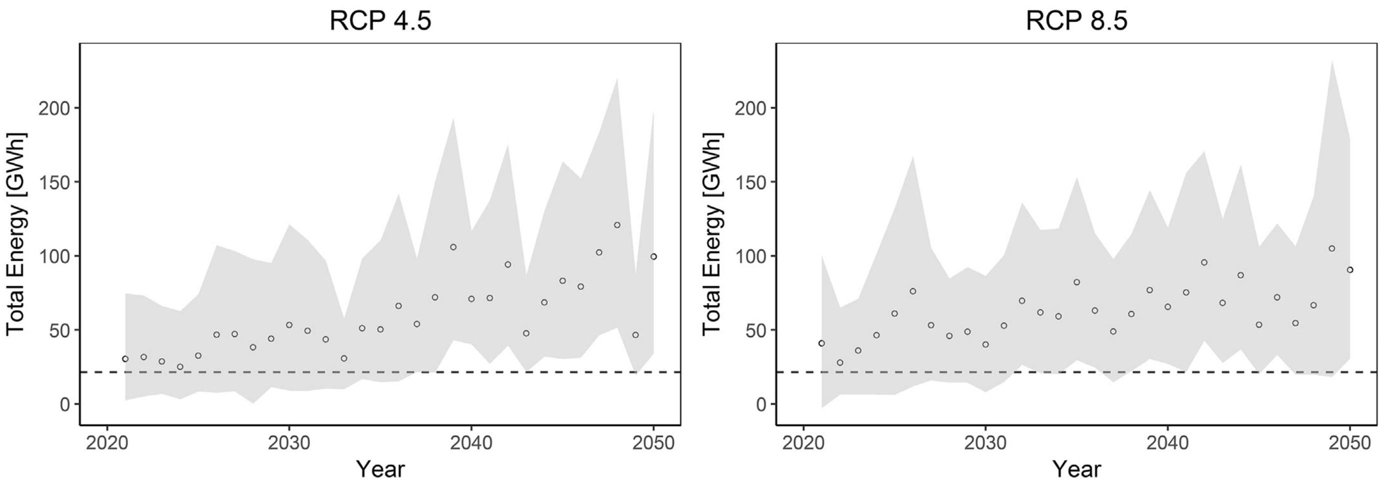


**Fig. 7.** Estimated total annual energy for cooling in Vienna with RCP 4.5 (left) and RCP 8.5 (right). The open circles are the ensemble average values. The grey band is the range of values at the 95% confidence level. The dashed line is the estimated total annual energy for cooling in 2016.

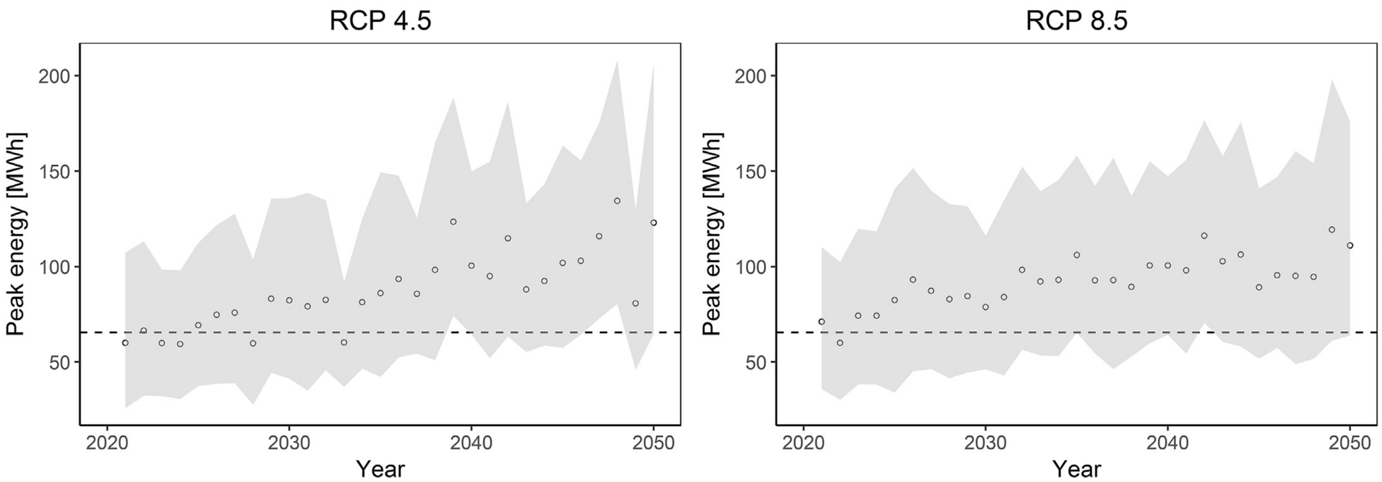


**Fig. 8.** Estimated peak annual energy for cooling in Vienna with RCP 4.5 (left) and RCP 8.5 (right). The open circles are the ensemble average values. The grey band is the range of values at the 95% confidence level. The dashed line is the estimated peak annual energy for cooling in 2016.

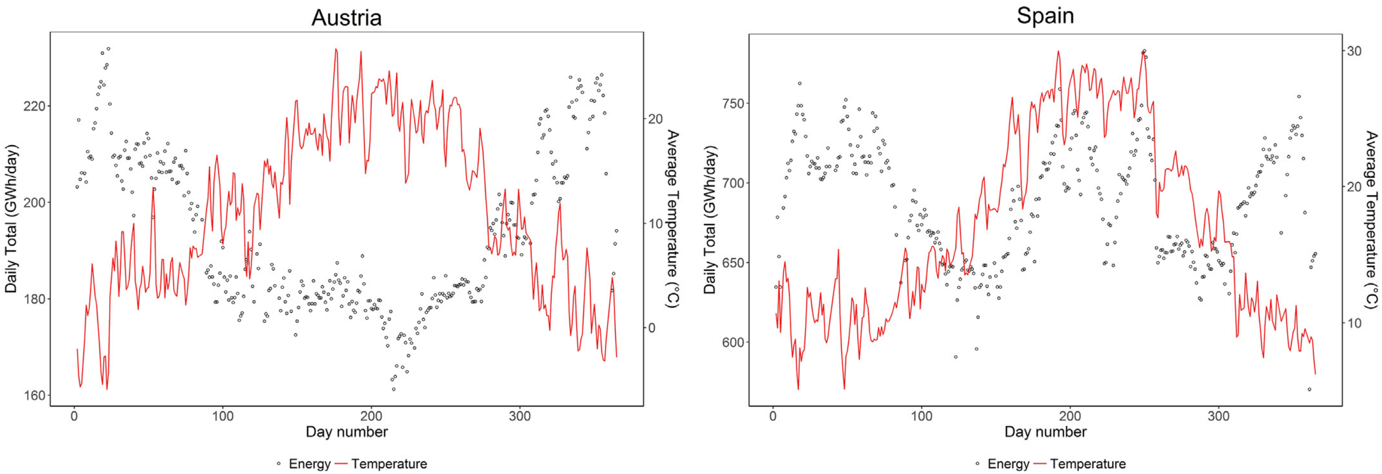


**Fig. 9.** Daily total electricity consumption and average temperature in 2016 for Austria (left) and Spain (right). The data display a significant decrease in electricity from day 200 to 250 due to summer vacations and industry downturn.

#### 4.3.1. Summer vacations

An issue of data quality is the handling of the decrease in electricity consumption due to the summer vacation industry downturn. Fig. 9 shows the daily temperature and electricity consumption for two countries (Austria and Spain). Both data show a significant decrease in electricity consumption between July 15 (day 197) and August 29 (day 242). Damm et al. (2017) chose to smooth the data to remove this “dip”. We chose to disregard these data by not including them in further analyses. However these data occur at roughly the time of maximum yearly temperature, hence including these data after some form of correction may strengthen the regression.

#### 4.3.2. Consumer behaviour correction

As mentioned previously, the bottom-up estimate method, in general, estimates the energy requirement for cooling as a multiplication of three components; the modelled specific energy demand (kWh/m$^2$) for a building or buildings; the total floor area in a country and the AC penetration rate. The last component is often taken as the ownership rate of AC equipment. However, this may overestimate the energy requirement because it does not consider consumer behaviour.

There are spatial and temporal complications that affect consumer behaviour and may not be captured in surveys – specifically residential surveys. For example, 2010 SERI Survey in Austria recorded that 4% of household own an AC unit, but the majority of these are single room units (S. Schwarzinger, personal communication), that may be used to cool a specific room only (e.g. the bedroom) – resulting in spatial misrepresentation. Hence, using the ownership rate as an indicator of AC penetration and multiplying it by the total floor area of the country may significantly over estimate the energy requirement (e.g. by a factor of 5–10 depending on household).

Two types of temporal complications may also affect consumer behaviour: 1) delayed AC use, and 2) time-average AC use. In the first case, older buildings in Austria tend to have thick walls with high thermal mass. These may affect consumer behaviour because there may be a delay before the interior of a residence is warm enough to warrant turning the AC unit on. Of course, the home owner will probably not use the AC when he/she is at work, after a specific hour at night, or early in the morning. Considering that the working day is 8 h, and the unit may not operate after midnight the actual time of use may be from 18:00 to 24:00 so an apparent penetration based on time average may be 25% of the actual AC ownership rate. Hence, Eq. (2) could be refined to include a consumer behaviour factor, $F_{CB}$.

$$E_{tot} = a_o + P_{AC} F_{CB} a_1 (T - T_0) \tag{7}$$

#### 4.3.3. Economic influences

Consumer behaviour may be influenced by many factors including specifically economic considerations. Returning to our assumption that to first order the penetration rate is dependent on climatic factors alone, some authors have included corrections for economic factors (e.g. Lam, 1998; Isaac and van Vuuren, 2009 and Wenz et al., 2017). We tested the $Slope_{max}$ in each year versus three different economic indicators; disposable income per capita, final consumption per capita and GDP per capita. We found no significant correlation when all 20 countries were considered. Nevertheless, qualitatively, it is clear that economic conditions influence $Slope_{max}$ for some countries. Fig. 10 shows $Slope_{max}$ versus $CDD_{max}$ and CDD for a range of years for the top eight countries. The $Slope_{max}$ versus CDD plot is difficult to interpret because there are changing CDD values and changing $F_{CB}$. The $Slope_{max}$ versus $CDD_{max}$ diagram show interesting patterns:

1) Serbia's (RS) economy remained relatively stable from 2009 to 2016;
2) Italy (IT) had a strong decrease in GDP in 2013 which corresponds with the low $Slope_{max}$;
3) Croatia (HR) experienced a slight decrease in GDP in 2013 and 2014;
4) The Spanish (ES) financial crisis occurred in 2012–2014 which also corresponds to a $Slope_{max}$ nadir. However, the economy had recovered well by 2016;
5) Montenegro's (ME) economy was relatively stable from 2009 to 2012, at which point it picked up considerably (approx. 4% growth p.a.) just as the $Slope_{max}$ did; and
6) The Greece (GR) financial crisis began in 2010. However, the economy has suffered since then and has not returned to its pre-2011 level. Nevertheless, the $Slope_{max}$ is higher in 2016 than in 2010, perhaps due to an increase in $CDD_{max}$

The pattern observed in Montenegro may be indicative of the pattern one might expect when penetration dynamics in absence of other factors (i.e. economic) are considered. Specifically, an increase in $CDD_{max}$ causes a slight increase in $Slope_{max}$ as the *initiators* start to “feel the heat” and buy AC units. This is followed by an increase in $Slope_{max}$ without an increase in $CDD_{max}$ as the *imitators* begin to see the advantages of installing AC. Unfortunately, in many countries, economic factors mask the postulated penetration dynamics.

#### 4.3.4. The $Slope_{max}$ dependency assumption

Clearly, the assumption that $Slope_{max}$ is related to penetration level only and that penetration level is related to $CDD_{max}$ is a simplification. Nevertheless, the fact that the $Slope_{max}$ versus $CDD_{max}$ has a good correlation ($r^2 = 0.824$) is empirical confirmation that the assumption is approximately correct. As mentioned in Eq. (2), $Slope_{max}$ should also depend on the thermal envelope and design of the buildings and energy efficiency of the cooling systems. So then, why does the assumption seem to hold?

The latter two components may not be very important. Due to roughly similar histories (i.e. World War II), the average age of

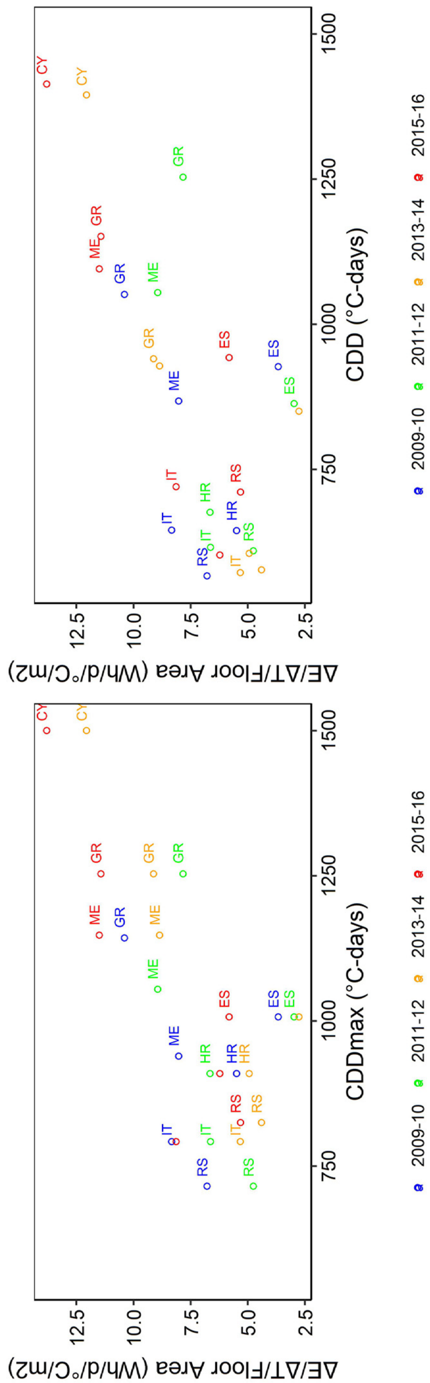


**Fig. 10.** Plots of $Slope_{max}$ versus $CDD_{max}$ (left) and CDD (right) for specific European countries colour-coded by year.

building stock in European countries is approximately constant. Based on the percentage of dwellings by age (ODYSSEE. Online database, 2018) the average age of dwellings in Austria, Bulgaria, Italy and Norway is 54 years. The average Spanish dwelling is somewhat younger at 43 years (self-calculation, unpublished). Hence the design of buildings is also roughly similar. In addition, since the EU is a common market, the energy efficiency of cooling systems will also be roughly similar across countries.

Thermal envelopes do vary from country to country in Europe. In colder countries, thermal envelopes have been improved to reduce energy for heating purposes. However, these improved envelopes will also reduce cooling demand on hot days. In hot countries (e.g. Greece or Spain) thermal envelopes have been improved to reduce energy for cooling. Nevertheless, the application of a country-dependent relative correction to $Slope_{max}$ to account for different thermal envelopes should probably reduce the variability in $Slope_{max}$. This is a possible direction for future research.

### *4.4. Implications for climate change adaptation strategies*

Many strategies have been identified which can help make cities cooler. These can be broadly categorised as strategies that increase the amount of shading and evaporative cooling (e.g. Memon et al., 2008; Oliveira et al., 2011; Theeuwes et al., 2013), changing the geometry of the city so that it is better ventilated (e.g. Middel et al., 2014) and changing building materials so that absorption of solar radiation and heat storage is reduced (e.g. Santamouris et al., 2012; Wang and Akbari, 2016). Of the many strategies, increasing the amount shading and evaporative cooling usually involves increasing the amount of green and blue infrastructure (i.e. vegetation and water surfaces) in the city. These nature-based solutions can bring additional benefits for the urban environment by potentially improving air quality (Akbari et al., 2001) and liveability (Horn and Xu, 2017). The effectiveness of some of these strategies in Vienna under the current climate has been studied by Žuvela-Aloise et al. (2016) and Žuvela-Aloise et al. (2018). The extension of this modelling to future climates is an item of current research.

As suggested by Kabisch et al. (2016) it is important that there is stronger evidence of the effectiveness of nature-based solution as an adaption strategy. The cost-effectiveness of these strategies should be considered from the point of view of society as a whole and not only from perspective of individual actors. The costs for implementing the strategies listed above would be borne by different stakeholders (e.g. private, business or governmental sectors) with different underlying priorities. In contrast, there are potential many risks of climate change without adaptation cited in the literature. These are mostly health related (Bartholy and Pongrácz, 2018; Ebi et al., 2018; Mika et al., 2018), and include mental health risks (Obradovich et al., 2018). Sometimes these are converted to costs (Takakura et al., 2017; Cai et al., 2018; Chiabai et al., 2018) which would mostly be carried by society. However, as the adoption of AC is possibly the simplest climate change adaptation strategy that an individual could implement, it must be questioned if it is a cost-effective strategy as compared to nature-based solutions for society as a whole. Hence there is the need to estimate of the total annual and peak daily electricity consumption for cooling with climate change including an increase in AC penetration. Furthermore, it should be added that the use of AC, when powered with fossil energy sources, contributes to the greenhouse effect. In addition, urban air temperatures have been shown to increase as a result of AC use (e.g. de Munck et al., 2013). Therefore, not only the cost-effectiveness, but effectiveness in general should be questioned when using AC as an adaptation strategy as opposed to nature-based solutions.

## 5. Conclusions

In this paper we have developed and applied a model to estimate the total annual and peak daily electricity consumption for cooling in Vienna until 2050. The model is based on top-down electric energy consumption measurements and maximum cooling degree-days ($CDD_{max}$) for 2015–2016. The model includes an estimate of the increase in AC penetration with climate change, based on the increase of $CDD_{max}$, and combines this with future daily average temperatures. The model is then applied to an ensemble of seven downscaled climate model estimates, for two scenarios, RCP4.5 and RCP8.5, for the area of Vienna. This approach is novel in that it a) includes the increase in AC penetration with climate change; b) estimates the peak daily electricity consumption in addition to the more usual total annual consumption; and c) the method is applied to a location rather than the country as a whole.

Our results suggests that electrical energy for cooling will increase from the current amount of 22 GWh/year to 95 (33–189) GWh/year by 2050 – with little difference during this time frame between RCP4.5 and RCP8.5 scenario. During the same period, peak electrical energy demand will increase to around 117 (64–191) MWh in 2050 from its current value of 65.5 MWh, again with no significant difference between RCP4.5 and RCP8.5 scenarios. The estimate has relatively large uncertainties ( ± 63%) primarily from two sources; the climate models ( ± 35%) and the modelling procedure itself ( ± 28%).

The modelling procedure could be refined to include factors that affect consumer behaviour (e.g. economy) in an attempt to reduce the uncertainty. However, based on the limited number of years studied (eight), uncertainty in the $Slope_{max}$ estimates, and lack of strong correlation, this was not attempted.

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## Declarations of interest

None.

## References

Akbari, H., Bretz, S., Hanford, J.W., Rosenfeld, A., Sailor, D.J., Taha, H., Bos, W., 1992. Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento municipal Utility District (SMUD) service area: project design and preliminary results. https://cloudfront.escholarship.org/dist/prd/content/qt84j1h3gz/qt84j1h3gz.pdf, Accessed date: 24 October 2018.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70 (3), 295–310.

Austria, Statistik, 2018. Beginning-Of-The-Year Population from 1952 to 2076. STATcube – Statistical Database of STATISTIK AUSTRIA. Available at. http://www.statistik.at/web_en/statistics/PeopleSociety/population/demographic_forecasts/index.html, Accessed date: 25 July 2018.

Bachner, G., Bednar-Friedl, B., Birk, S., Feichtinger, G., Gobiet, A., Gutschi, C., Heinrich, G., Kulmer, V., Leuprecht, A., Prettenthaler, F., Rogler, N., Schinko, T., Schüppel, A., Stigler, H., Themeßl, M., Töglhofer, C., Wagner, T., 2013. Impacts of climate change and adaptation in the electricity sector–the case of Austria in a continental European context (EL. ADAPT). Wegener Center scientific report 51-2013. Wegener Center Verlag, Graz.

Bartholy, J., Pongrácz, R., 2018. A brief review of health-related issues occurring in urban areas related to global warming of 1.5° C. Curr. Opin. Environ. Sustain. 30, 123–132.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15, 215–227. https://doi.org/10.1287/mnsc.15.5.215.

Berger, T., Amann, C., Formayer, H., Korjenic, A., Pospichal, B., Neururer, C., Smutny, R., 2014. Impacts of urban location and climate change upon energy demand of office buildings in Vienna, Austria. Build. Environ. 81, 258–269. https://doi.org/10.1016/j.buildenv.2014.07.007.

Blazquez, L., Boogen, N., Filippini, M., 2013. Residential electricity demand for Spain: new empirical evidence using aggregated data. Energy Econ. 36, 648–657. https://doi.org/10.1016/j.eneco.2012.11.010.

Cai, X., Lu, Y., Wang, J., 2018. The impact of temperature on manufacturing worker productivity: evidence from personnel data. J. Comp. Econ. 46 (4), 889–905.

Chiabai, A., Spadaro, J., Neumann, M., 2018. Valuing deaths or years of life lost? economic benefits of avoided mortality from early heat warning systems. Mitig. Adapt. Strateg. Glob. Chang. 1–18.

Christenson, M., Manz, H., Gyalistras, D., 2006. Climate warming impact on degree-days and building energy demand in Switzerland. Energy Convers. Manag. 47, 671–686. https://doi.org/10.1016/j.enconman.2005.06.009.

Damm, A., Köberl, J., Prettenthaler, F., Rogler, N., Töglhofer, C., 2017. Impacts of +2°C global warming on electricity demand in Europe. Clim. Serv. 7, 12–30. https://doi.org/10.1016/j.cliser.2016.07.001.

Davis, L.W., Gertler, P.J., 2015. Contribution of air conditioning adoption to future energy use under global warming. Proc. Natl. Acad. Sci. 112, 5962–5967. https://doi.org/10.1073/pnas.1423558112.

De Rosa, M., Bianco, V., Scarpa, F., Tagliafico, L., 2014. Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach. Appl. Energy 128, 217–229. https://doi.org/10.1016/j.apenergy.2014.04.067.

De Wit, R., Zuvela-Aloise, M., Andre, K., Bird, D.N., Schwaiger, H., Kolb, F., Peharz, G., 2017. Quantifying the Potential of Photonic Cooling to Improve Urban Microclimate Presented at RealCorp Conference, 12.-15.9.2017; Vienna., RealCorp Conference, 12.-15.9.2017; Vienna., 2017. http://repository.corp.at/368/1/CORP2017_44.pdf, Accessed date: 25 July 2018.

Diogo V, Koomen E (2014) Simulating future changes in the urban heat island effect based on an integration of socio-economic and climate scenarios, In Adaptation Frontiers - conference on european climate change adaptation research and practice. http://www.adaptationfrontiers.eu/pdf/A-H-03-VDiogo.pdf. Accessed 25 July 2018.

Ebi, K., Hasegawa, T., Hayes, K., Monaghan, A., Paz, S., Berry, P., 2018. Health risks of warming of 1.5° C, 2° C, and higher, above pre-industrial temperatures. Environ. Res. Lett. 13 (6), 063007.

ENTSO-E: European Network of Transmission System Operators for Electricity, 2018. Power statisticsAvailable at. https://www.entsoe.eu/data/statistics/Pages/default.aspx, Accessed date: 25 July 2018.

EPA: United States Environmental Protection Agency, 2016. Technical Documentation: Heating and Cooling Degree Days. https://www.epa.gov/sites/production/files/2016-08/documents/heating-cooling_documentation.pdf, Accessed date: 25 October 2018.

Eto, J.H., 1988. On using degree-days to account for the effects of weather on annual energy use in office buildings. Energy Build. 12, 113–127. https://doi.org/10.1016/0378-7788(88)90073-4.

European Commission, 2018. EU Buildings Database. https://ec.europa.eu/energy/en/eu-buildings-database, Accessed date: 25 July 2018.

European Environment Agency (EEA), 2017. Climate change adaptation and disaster risk reduction in Europe enhancing coherence of the knowledge base, policies and practices. Report No. 15/2017. https://www.eea.europa.eu/publications/climate-change-adaptation-and-disaster/at_download/file, Accessed date: 25 July 2018.

eurostat, 2018a. Population on 1 January by age Groups and Sex - cities and greater Cities [urb_cpop1]. Available at. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=urb_cpop1&lang=en, Accessed date: 23 October 2018.

eurostat, 2018b. Population change - demographic balance and crude rates at national level [demo_gind]. Available at. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_gind&lang=en, Accessed date: 25 July 2018.

Giannakopoulos, C., Psiloglou, B.E., 2006. Trends in energy load demand for Athens, Greece: weather and non-weather related factors. Clim. Res. 31, 97–108.

Horn, O., Xu, Q., 2017. Nature-Based Solutions for Sustainable Urban Development. (ICLEI – Local Governments for Sustainability).

IPCC, 2001. Glossary to the Third Assessment Report. http://www.ipcc.ch/pdf/glossary/tar-ipcc-terms-en.pdf, Accessed date: 25 October 2018.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge university press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/CBO9781107415324. (1535 pp).

Isaac, M., van Vuuren, D., 2009. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37, 507–521. https://doi.org/10.1016/j.enpol.2008.09.051.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Jakubcionis, M., Carlsson, J., 2017. Estimation of European Union residential sector space cooling potential. Energy Policy 101, 225–235. https://doi.org/10.1016/j.enpol.2016.11.047.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol. Soc. 21 (2), 39. https://doi.org/10.5751/ES-08373-210239.

Kikegawa, Y., Chenchi, Y., Yoshikado, H., Kondo, H., 2003. Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings' energy-demands. Appl. Energy 76, 449–466. https://doi.org/10.1016/S0306-2619(03)00009-6.

Ko, Y., 2013. Urban form and residential energy use: a review of design principles and research findings. J. Plan. Lit. 28 (4), 327–351. https://doi.org/10.1177/0885412213491499.

Lam, J.C., 1998. Climatic and economic influences on residential electricity consumption. Energy Convers. Manag. 39, 623–629. https://doi.org/10.1016/S0196-8904(97)10008-5.

Le Comte, D.M., Warren, H.E., 1981. Modeling the impact of summer temperatures on national electricity consumption. J. Appl. Meteorol. 20, 1415–1419.

Lundgren, K., Kjellstrom, T., 2013. Sustainability challenges from climate change and air conditioning use in urban areas. sustainability. Multidiscip. Digit. Publ. Inst. 2013 (5), 3116–3128. https://doi.org/10.3390/su5073116.

Memon, A.R., Leung, Y.C.D., Chunho, L., 2008. A review on the generation, determination and mitigation of urban heat island. J. Environ. Sci. 20 (1), 120–128.

Middel, A., Hab, K., Brazel, A.J., Martin, C.A., Guhathakurta, S., 2014. Impact of urban form and design on mid-afternoon microclimate in phoenix local climate zones. Landsc. Urban Plan. 122, 16–28.

Mika, J., Forgo, P., Lakatos, L., Olah, A., Rapi, S., Utasi, Z., 2018. Impact of 1.5 K global warming on urban air pollution and heat island with outlook on human health effects. Curr. Opin. Environ. Sustain. 30, 151–159.

Moral-Carcedo, J., Vicéns-Otero, J., 2005. Modelling the non-linear response of Spanish electricity demand to temperature variations. Energy Econ. 27, 477–494. https://doi.org/10.1016/j.eneco.2005.01.003.

Mueller, A., Kranzl, L., Hummel, M., Toleikyte, A., Neusser, M., Gladt, M., Bednar, T., Schicker, I., Formayer, H., 2014. Impact of Climate Change on Heating and Cooling Demand in Buildings: Analysis of the Austrian Case. Austrian Climate Research Program. https://www.eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/research/downloads/PR_356_07_PRESENCE_heating&cooling_working_paper.pdf, Accessed date: 25 July 2018.

de Munck, C., Pigeo, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., Merchat, M., Poef, P., Marchadier, C., 2013. How much can air conditioning increase air temperatures for a city like Paris, France? Int. J. Climatol. 33, 210–227. https://doi.org/10.1002/joc.3415.

NOAA: National Oceanographic and Atmospheric Administration, 2018a. Degree Days Explanation. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/ddayexp.shtml, Accessed date: 25 October 2018.

NOAA: National Oceanographic and Atmospheric Administration, 2018b. Climate Data Online. Available at. https://www.ncdc.noaa.gov/cdo-web/, Accessed date: 25 July 2018.

Obradovich, N., Migliorini, R., Paulus, M., Rahwan, I., 2018. Empirical evidence of mental health risks posed by climate change. Proc. Natl. Acad. Sci. 115 (43), 10953–10958.

ODYSSEE. Online database, 2018. http://www.odyssee-mure.eu, Accessed date: 25 July 2018.

Ohashi, Y., Genchi, Y., Kondo, H., Kikegawa, Y., Yoshikado, H., Hirano, Y., 2006. Influence of air conditioning waste heat on air temperature in Tokyo during summer: numerical experiments using an urban canopy model coupled with a building energy model. J. Appl. Meteorol. Climatol. 46, 66–81. https://doi.org/10.1175/JAM2441.1.

Oliveira, S., Andrade, H., Vaz, T., 2011. The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. Build. Environ. 46, 2186–2194.

Parker, J.H., 1983. Landscaping to reduce the energy used in cooling buildings. J. For. 81 (2), 82–105.

Peharz, G., Kolb, F., Beermann, M., Bird, D.N., Schwaiger, H., de Wit, R., Zuvela-Aloise, M., Andre, K., 2018. Photonic cooling – Effizientere Gebäudekühlung durch Nutzung von Photonik. Final project report, published by Austrian Ministry for Transport, Innovation and Technology. https://nachhaltigwirtschaften.at/de/sdz/projekte/photonic-cooling.php, Accessed date: 25 July 2018.

Persson, U., Werner, S., 2015. Quantifying the Heating and Cooling Demand in Europe: work Package 2, Background Report 4 of the STRATEGO project (Multi-level actions for enhanced heating & cooling plans). http://stratego-project.eu, Accessed date: 25 July 2018.

Pezzutto, S., Sparber, W., Fedrizzi, R., 2014. Analysis of the space heating and cooling market in Europe. Methods 12 (13), 14. http://www.eurac.edu/en/research/technologies/renewableenergy/publications/Documents/Paper%20for%20the%203rd%20International%20PhD-Day%20Linz_Simon%20Pezzutto_final%20version_to%20publish.pdf, Accessed date: 24 October 2018.

Sailor, D.J., Muñoz, J.R., 1997. Sensitivity of electricity and natural gas consumption to climate in the USA—methodology and results for eight states. Energy 22, 987–998. https://doi.org/10.1016/S0360-5442(97)00034-0.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., Wang, M., 2014. Anthropogenic heating of the urban environment due to air conditioning. JGR-Atmos. 119, 5949–5965. https://doi.org/10.1002/2013JD021225.

Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Giannopoulou, K., Vasilakopoulou, K., Kardomateas, T., 2012. Using cool paving materials to improve microclimate of urban areas - design realization and results of the flisvos project. Build. Environ. 53, 128–136.

Simpson, J.R., McPherson, E.G., 1996. Potential of tree shade for reducing residential energy use in California. J. Arboric. 22, 10–18.

Sivak, M., 2013. Will AC put a chill on the global energy supply? Am. Sci. 101, 330. https://doi.org/10.1511/2013.104.330.

Smith, K.R., Woodward, A., Campbell-Lendrum, D., Chadee, D.D., Honda, Y., Liu, Q., Olwoch, J.M., Revich, B., Sauerborn, R., 2014. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Human health: impacts, adaptation, and co-benefits. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University, 2014, Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709–754. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap11_FINAL.pdf, Accessed date: 25 July 2018.

Takakura, J., Fujimori, S., Takahashi, K., Hijioka, Y., Hasegawa, T., Honda, Y., Masui, T., 2017. Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation. Environ. Res. Lett. 12 (6), 064010.

Theeuwes, N.E., Solcerova, A., Steeneveld, G.J., 2013. Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. J. Geophys. Res.-Atmos. 118, 8881–8896.

Töglhofer, C., Habsburg-Lothringen, C., Prettenthaler, F., Rogler, N., Themessl, M., 2012. EL.ADAPT: Impacts of Climate Change on Electricity Demand. https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2012/files/pr/PR_Toeglhofer.pdf, Accessed date: 25 July 2018.

USGCRP: The U.S. Global Change Research Program, 2018. Heating and Cooling Degree Days. https://www.globalchange.gov/browse/indicators/indicator-heating-and-cooling-degree-days, Accessed date: 25 October 2018.

Vahmani, P., Sun, F., Hall, A., Ban-Weiss, G., 2016. Investigating the climate impacts of urbanization and the potential for cool roofs to counter future climate change in Southern California. Environ. Res. Lett. 11, 124027.

Valor, E., Meneu, V., Caselles, V., 2001. Daily air temperature and electricity load in Spain. J. Appl. Meteorol. 40, 1413–1421. https://doi.org/10.1175/1520-0450(2001)040<1413:DATAEL>2.0.CO;2.

Wang, Y., Akbari, H., 2016. Analysis of urban heat island phenomenon and mitigation solutions evaluation for Montreal. Sustain. Cities Soc. 26, 438–446.

Wenz, L., Levermann, A., Auffhammer, M., 2017. North–south polarization of European electricity consumption under future warming. Proc. Natl. Acad. Sci. 114, E7910–E7918. https://doi.org/10.1073/pnas.1704339114.

Werner, S., 2016. European space cooling demands. Energy 110, 148–156. https://doi.org/10.1016/j.energy.2015.11.028.

World Meteorological Organisation (WMO), 2015. In: McGregor, G.R., Bessemoulin, P., Ebi, K., Menne, B. (Eds.), Heatwaves and health: guidance on warning-system development, 2015, WMO Report 1142. http://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf, Accessed date: 25 July 2018.

Žuvela-Aloise, M., Koch, R., Buchholz, S., Früh, B., 2016. Modelling the potential of green and blue infrastructure to reduce urban heat load in the city of Vienna. Clim. Chang. https://doi.org/10.1007/s10584-016-1596-2.

Žuvela-Aloise, M., Andre, K., Schwaiger, H., Bird, D.N., Gallaun, H., 2018. Modelling reduction of urban heat load in Vienna by modifying surface properties of roofs. Theor. Appl. Climatol. 131 (3–4), 1005–1018.